

Ion Propulsion's Impact on Space Exploration

March 23, 2018

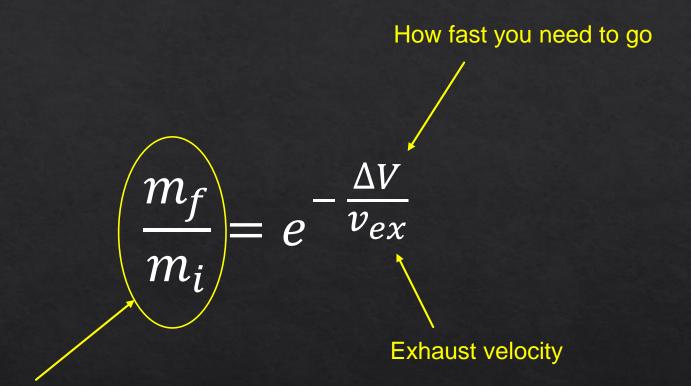
John Brophy
Jet Propulsion Laboratory
California Institute of Technology



Past



Rocket Equation



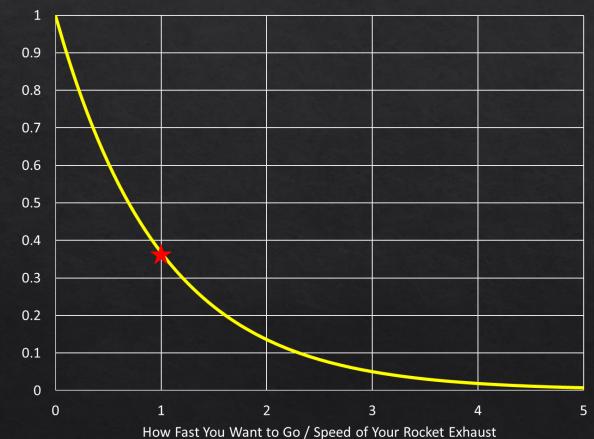
What you have left over that's not propellant



Fraction of What You Started With

Rocket Equation

If your exhaust velocity is about the same speed you want your spacecraft to go then nearly 2/3rds of your initial mass is propellant

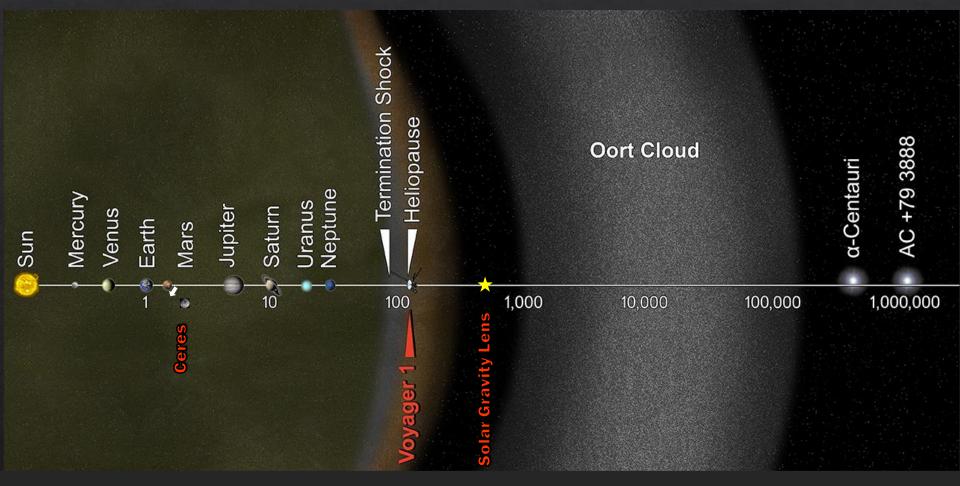








Space is BIG



Past: ΔV 's of $\sim 1 \text{ km/s}$ Present: ΔV 's of $\sim 10 \text{ km/s}$ Future: ΔV 's of $\sim 100 \text{ km/s}$



Rocket Equation

$$\frac{m_f}{m_i} = e^{-\frac{\Delta V}{I_{Sp}g}}$$
Specific Impulse



Specific Impulse

For a propellant mass that weighs 1 N at the Earth's surface, How long can you sustain a thrust of 1 N?

Thrust:
$$T = \dot{m}v_{ex}$$

Time to exhaust all the propellant: $t = \frac{M_p}{\dot{m}}$

$$W_p = M_p g \to M_p = \frac{W_p}{g}$$

$$t = \frac{W_p v_{ex}}{Tg}$$

for
$$W_p = T = 1$$
, then $t = \frac{v_{ex}}{g} \equiv I_{sp}$

JPL

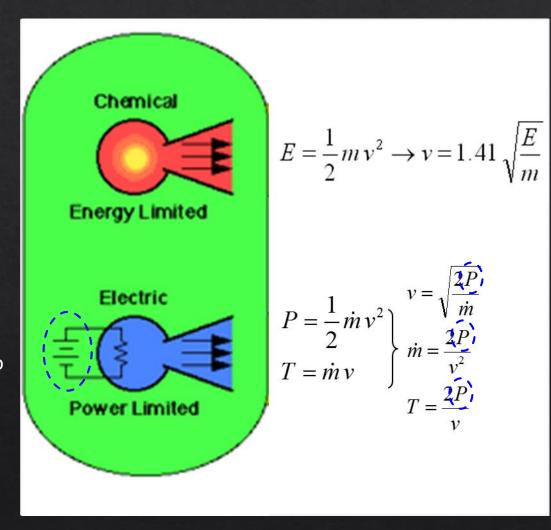
Chemical vs Electric Propulsion

Chemical propulsion systems:

- Carry the energy for propulsion with the propellant
- Power is determined by the propellant mass flow rate
- Performance is limited by the energy density of the propellants

Electric propulsion systems:

- Decouple the energy for propulsion from the propellants – allows more energy to be added to each kg of propellant
- Power is generated on-board by a separate power system
- Performance is limited by the power generated by the power system



Three Types of Electric Thrusters

► Electrothermal → resistively heat the propellant and expand the hot gas through a nozzle



➤ <u>Electrostatic</u> → ionize the propellant and accelerate the ions through an electric field

Gridded Ion Thrusters

William Front Care

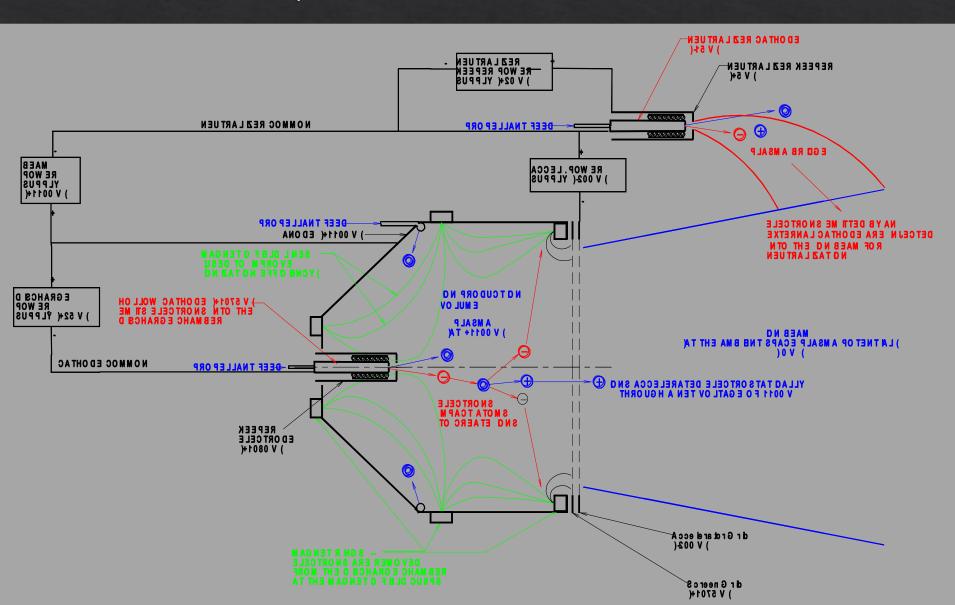
► Electromagnetic → ionize the propellant and accelerate the ions using crossed electric and magnetic fields





Ion Thruster Operation

Ionize the Propellant, Accelerate the Ions, Neutralize the Ion Beam





Present



Specific Impulse

Mono-propellant hydrazine thruster



$$Isp = 220 s$$

Bi-propellant NTO/MMH



$$Isp = 320 s$$

Bi-propellant LOX/LH2



$$Isp = 450 s$$

Aerojet XR5 Xenon Hall Thruster



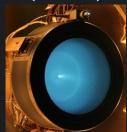
Isp = 2000 s

Xenon Ion Thruster (Dawn)



$$Isp = 3100 s$$

Xenon Ion Thruster (NEXT)



$$Isp = 4000 s$$



Commercial Spacecraft

OPERATIONAL SATELLITES WITH ELECTRIC PROPULSION

9/18/2013





ALL SPACECRAFT EMPLOYING EP = 236 SPACECRAFT EMPLOYING AEROJET ROCKETDYNE EP = 148



Boeing All Electric Satellites

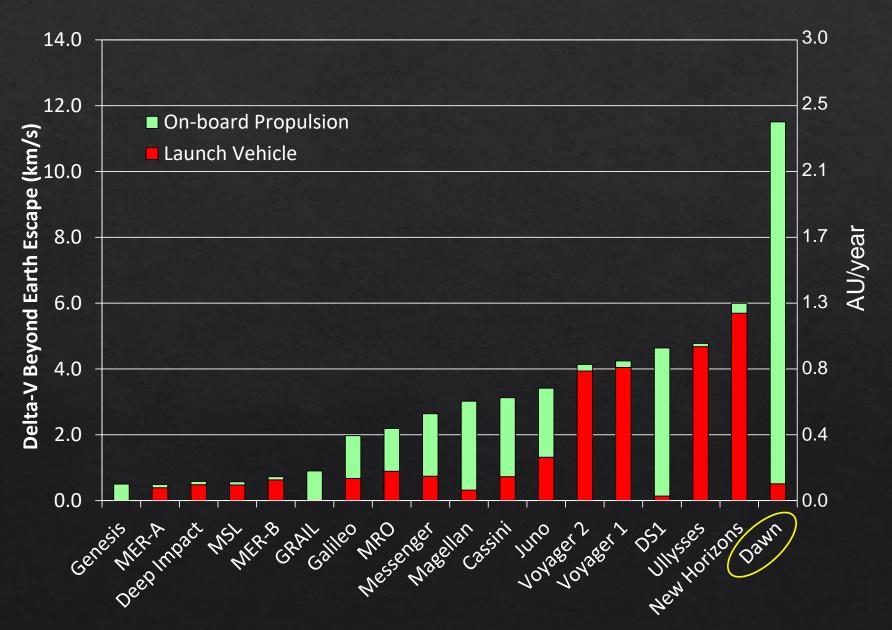




Deep Space Missions



AV Beyond Earth Escape



Dawn BY THE NUMBERS

48,000 HOURS OF ION ENGINE THRUSTING

132+ GB SCIENCE DATA COllected

2,450 orbits around Vesta and Ceres

11 km/s ΔV

69,000 images taken

3.5 BILLION MILES TRAVELED since launch

2 new worlds EXPLORED







Deep Space Missions using Electric Propulsion





Future

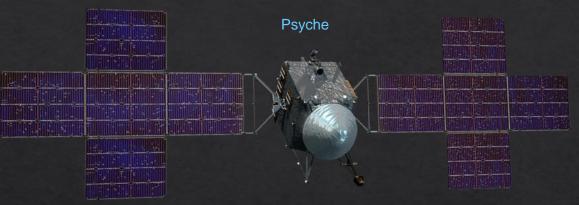


Potential Future Applications

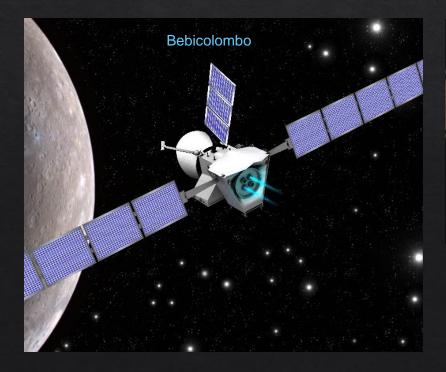
- Robotic Science Missions
- Human Exploration Missions
- Planetary Defense
- Asteroid Mining
- Interstellar Precursor Missions



Robotic Science Missions



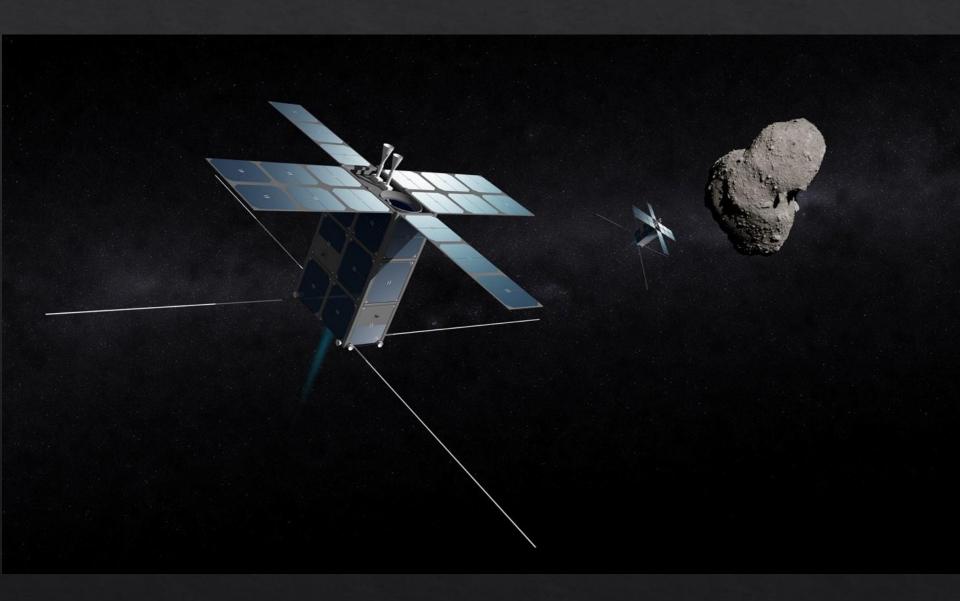








Deep Space SmallSats





Low-Power Hall Thrusters

- ♦ 500-W Hall thruster
- Magnetically-shielded Miniature (MASMI) Hall Thruster
 - With a centrally-mounted hollow cathode
- Key Issues
 - ♦ Performance
 - ★ Life Qualification



Targeted for deep-space science missions with small spacecraft (~100 kg)



Extreme SEP

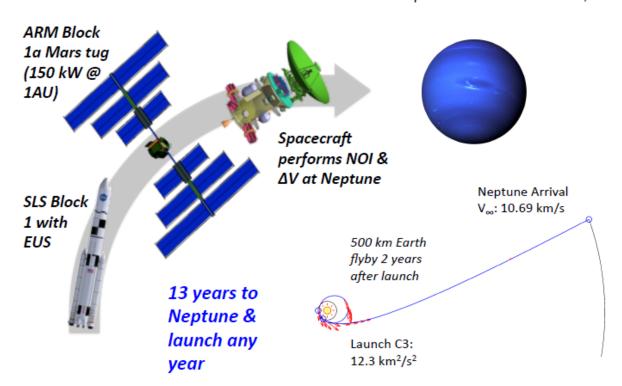
Damon Landau (JPL) and Nathan Strange (JPL)

SUS+ARM Neptune Flagship

SLS+ARM could deliver 4,500 kg to Neptune orbit in 13 yrs.

This is 3X the mass of a comparable chemical propulsion trajectory.

Neptune Arrival Mass 20,260 kg
SEP Tug Mass 8,000 kg
NOI Propellant (bi-prop) 7,760 kg
Mass in Neptune Orbit 4,500 kg

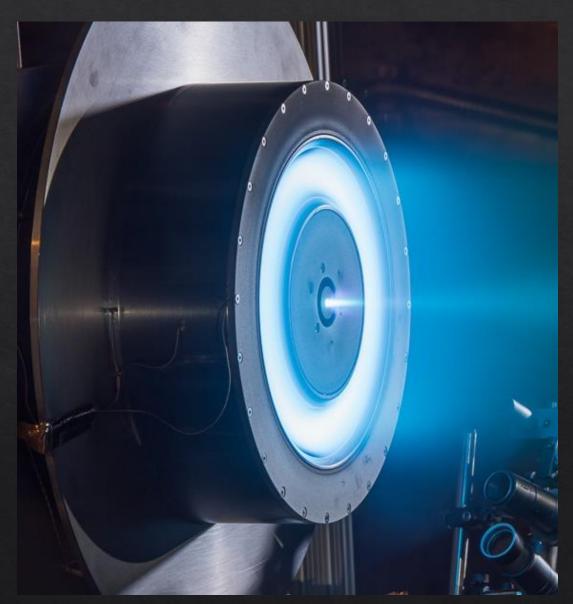




High-power Hall Thrusters

HERMES Hall Thruster

- ♦ 12.5-kW, 2600-s Hall Thruster
- Currently under development by NASA / Aerojet Rocketdyne
- ♦ Key Issues
 - > Performance
 - Life Qualification
 - > Spacecraft Interactions

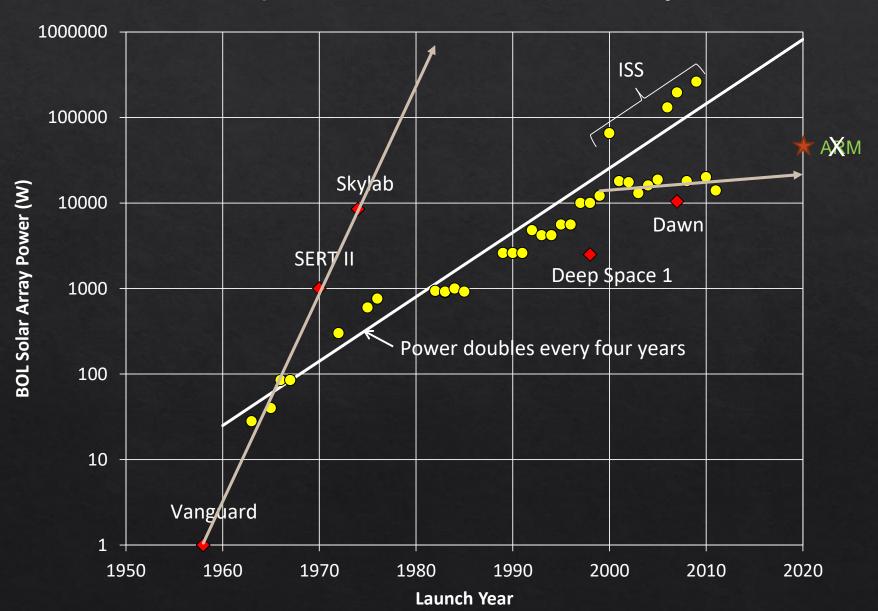


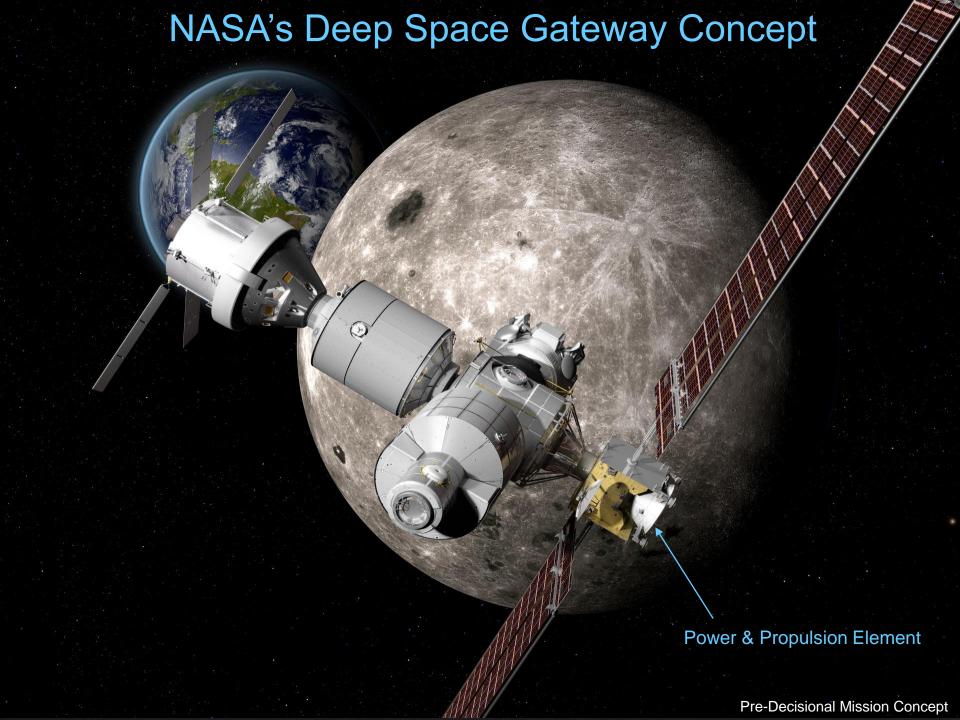


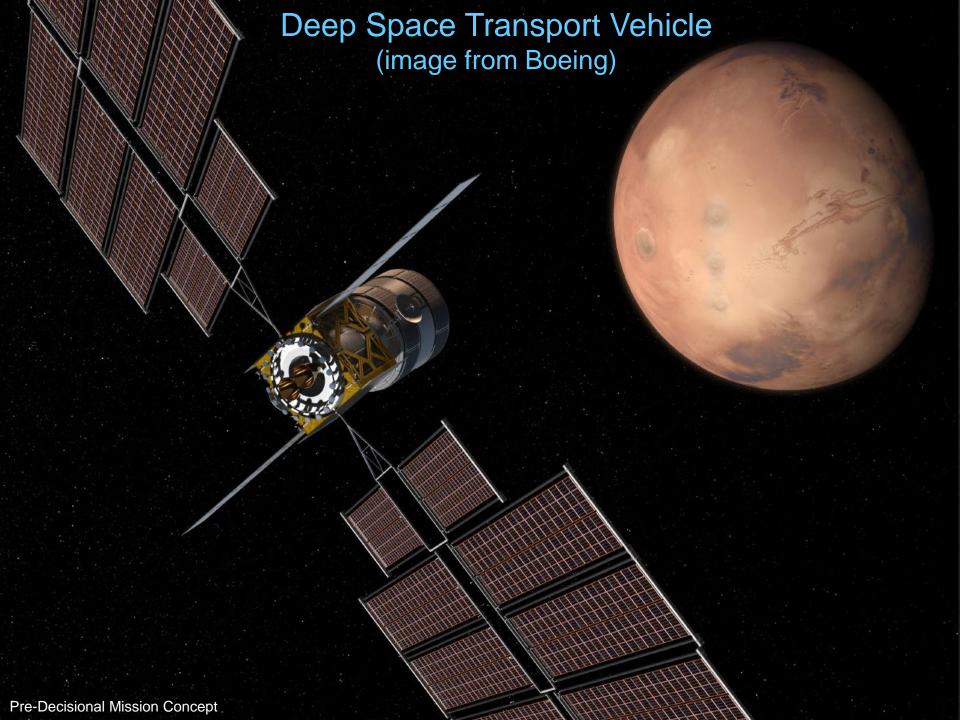
Human Exploration Beyond Low-Earth Orbit



It's All About Power Space Solar Power History









High-power Hall Thrusters

NEXTStep 100-kW Hall

Operate for 100 hrs at 100 kW





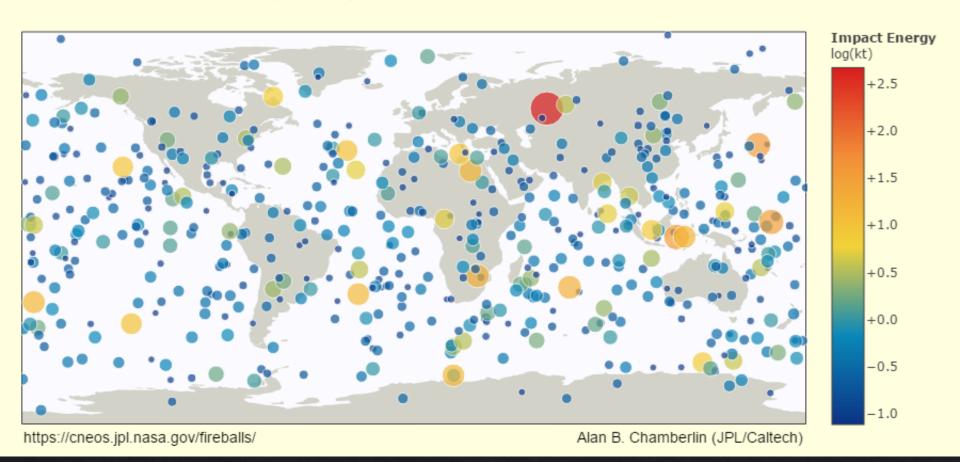
Planetary Defense

- > After discovery, this becomes primarily a propulsion problem
- What size asteroids do we need to be concerned with?



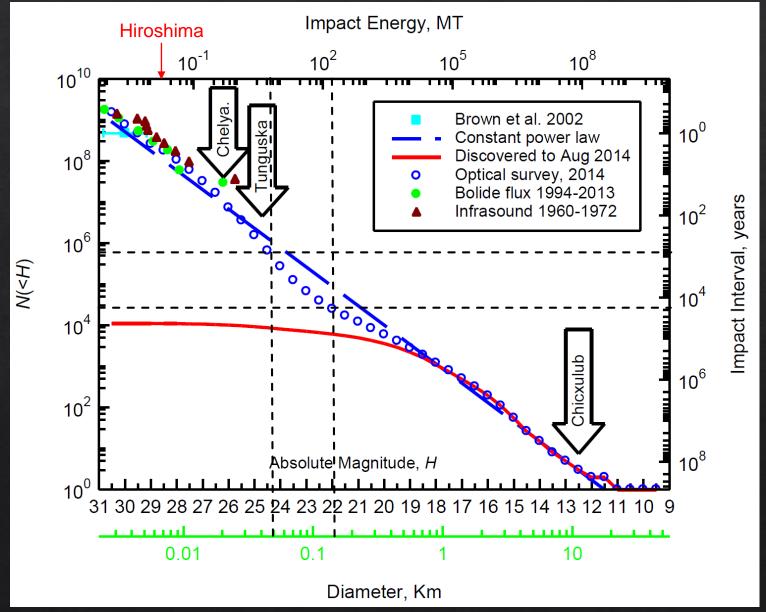
Fireballs Reported by US Government Sensors

(1988-Apr-15 to 2017-Mar-11)



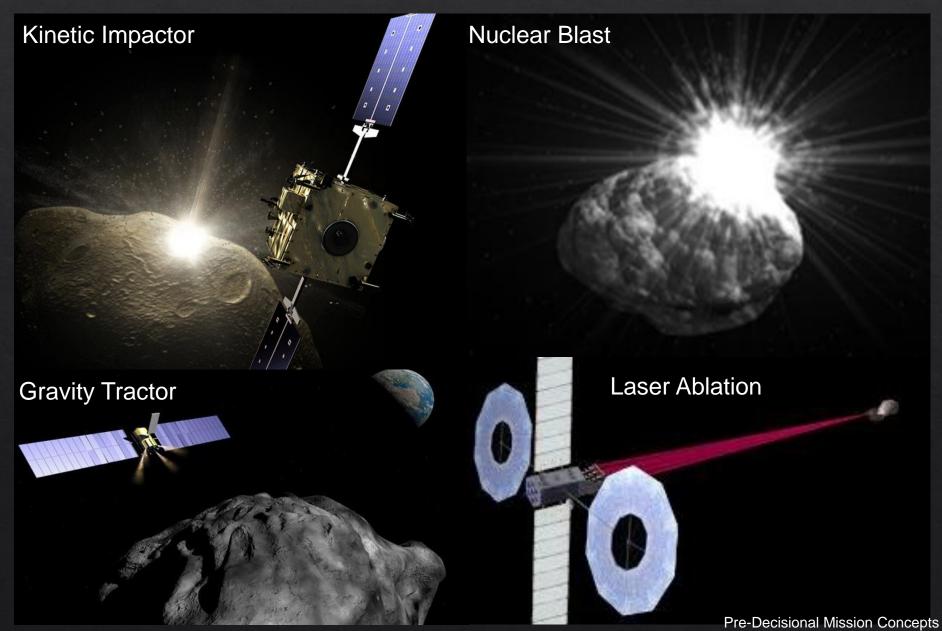


NEA Size-Frequency Distribution





Planetary Defense Techniques

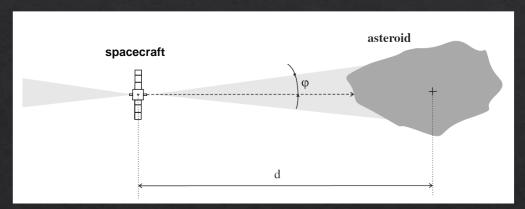


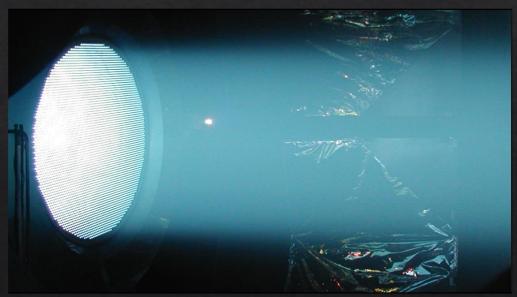


Ion Beam Deflection

Key Features

- Applied force is essentially independent of the asteroid characteristics
- lons act as kinetic impactors
- Can engineer the applied force (power) and propellant usage (specific impulse)
- Must thrust in opposite directions simultaneously
- Enables large stand-off distance from the asteroid
 - Requires small ion beam divergence angle





Key Technology is to design ion optics to provide < 3 degree ion beam divergence

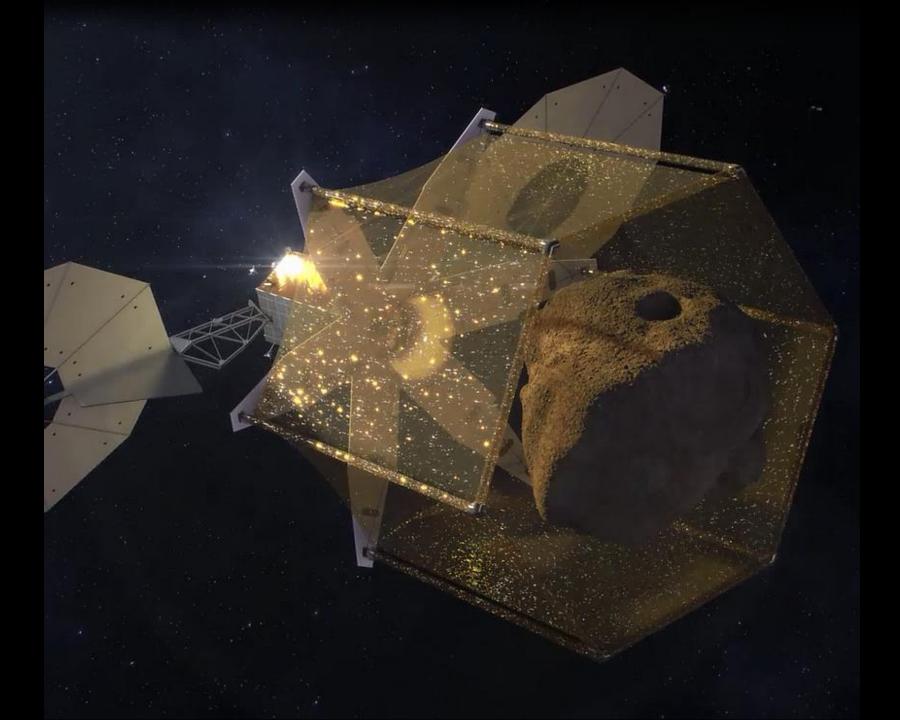


Asteroid Mining

- Has long been recognized as a propulsion problem
- Probably only feasible in the long run if you can use asteroid-derived propellants

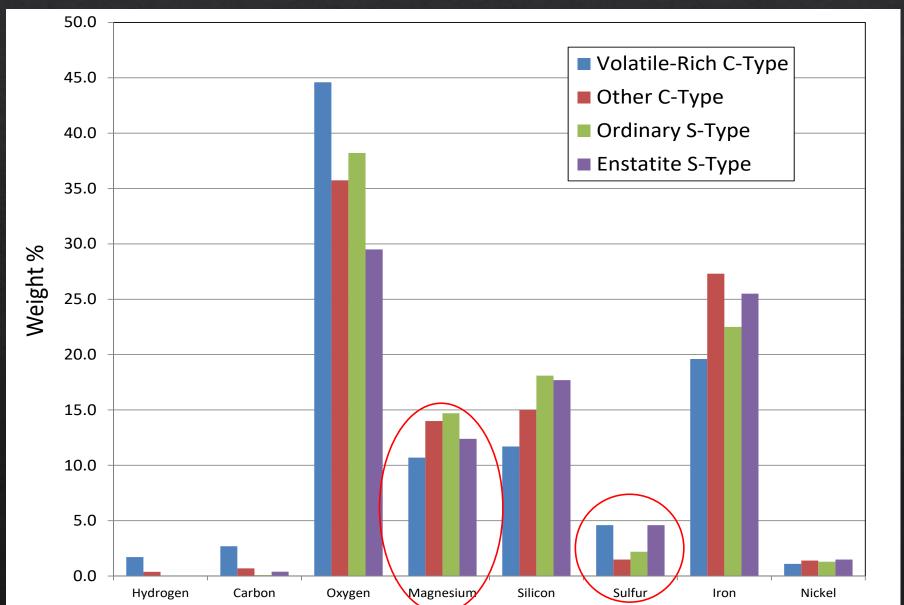
Past proposals include:

- Water
- Mass drivers (throwing rocks)
- Even billards (colliding one NEA with another)





What are Asteroids Made of?



Hutchison, R., "Meteorites, A Petrologic, Chemical and Isotopic Synthesis," Cambridge University Press, 2004, ISBN 0521470102.

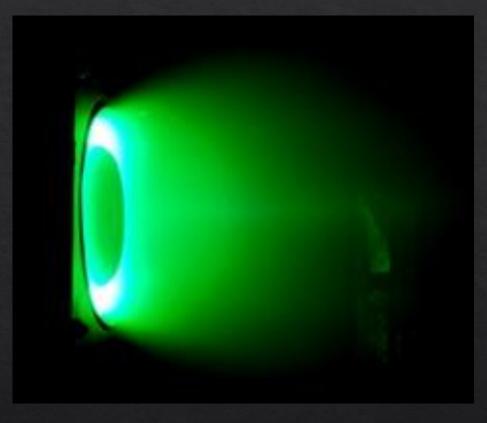


Asteroid-Derived Hall Thruster Propellants

State-of-the-art flight Hall thrusters use xenon as the propellant, but laboratory tests have also demonstrated operation on argon, krypton, iodine, and bismuth.

What about magnesium?

A magnesium-fueled Hall thruster from Michigan Technological University



	Molecular	Melting	Boiling	Ionization Energy						
	Weight	Point	Point	(eV)			Vapor Pressure			
	(AMU)	(C)	(C)	1st	2nd	Temperature	1 Pa	10 Pa	100 Pa	1000 Pa
Magnesium	24.31	650	1091	7.65	15.04	T (K)	701	773	861	971
Sulfur	32.06	115	445	10.36	23.34	T (K)	375	408	449	508
Xenon	131.3	-112	-108	12.13	21.21	T (K)	83	92	103	117



Ultra-High ΔV Missions



Solar Gravity Lens Mission Concept

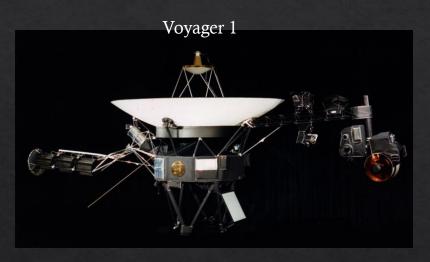
Want to go to > 550 AU in less than 15 years (~40 AU/year)





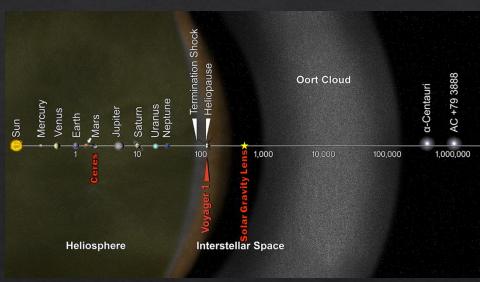


Must Go Faster



3.6 AU/year

- Voyager 1 is the fastest spacecraft in history
- Would take 150 years to get to the solar gravity lens focus at 550 AU



- We want to go 10x faster than Voyager 1, or about 40 AU/year
- How can we do this?



Solar Gravity Lens Focus





Three Key Features of Our Proposed Architecture to Go Fast

1

High Power

2

Small Mass

3

Not a Lot of Propellant



Don't carry the power source— laser beam power to the spacecraft

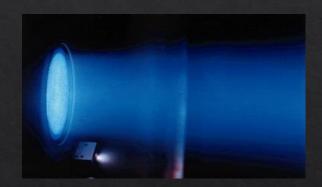


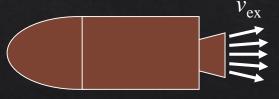
Artist's concepts



Collect the laser power and convert it to electricity to power the ion drive system

Pre-Decisional Mission Concept





Increase the exhaust velocity, $v_{\rm ex}$ by a factor of 10 over the best ion engines today

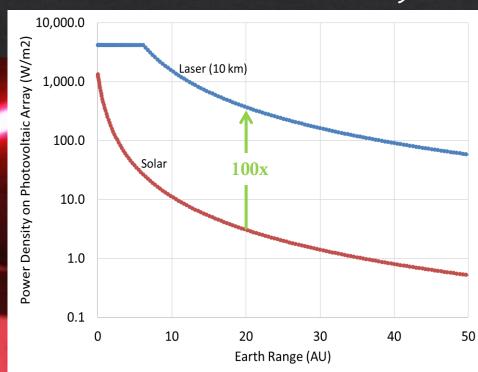


LASER

High-power, space-based laser

- Phased array
- Kilometer-scale aperture
- 100's of megawatts

Beam Power Across the Solar System





Popular Mechanics

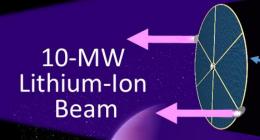
Humanity's Biggest Machines Will Be Built in Space

By Avery Thompson, Feb 16, 2018

"A mile-wide satellite might sound impossible, but that's exactly where the space industry is headed."







Spacecraft with 110-m dia. photovoltaic array tuned to the laser frequency

Space-based laser powers a 40,000-s Isp vehicle past Jupiter on a 13-year trip to 550 AU

Artist's concept

Pre-Decisional Mission Concept



110-m diameter Photovoltaic Array Areal density < 200 g/m²

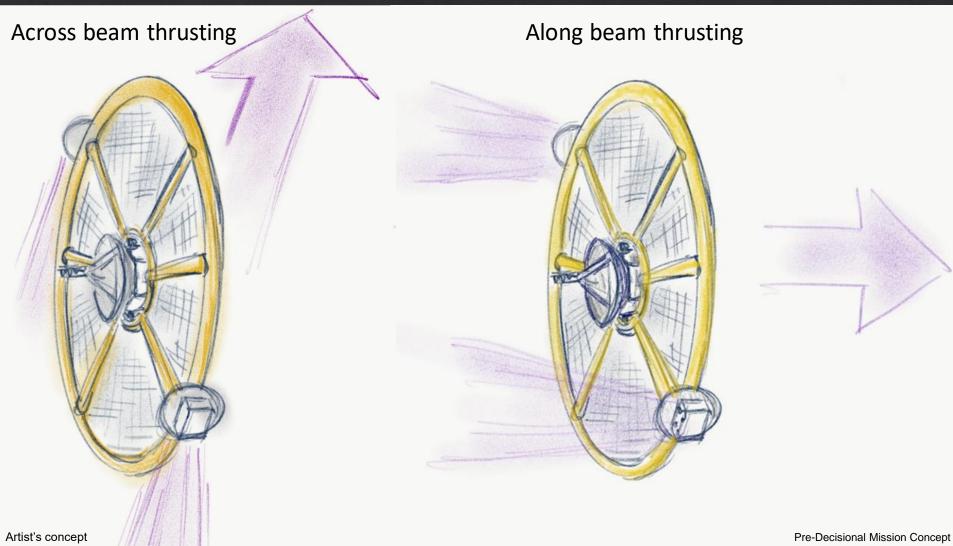
Lithium-fueled ion engines



Array cells tuned to the laser frequency for efficiency > 50%

Array output voltage of 6 kV



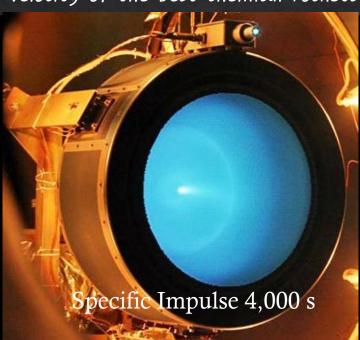




Lithium-fueled Ion Thruster

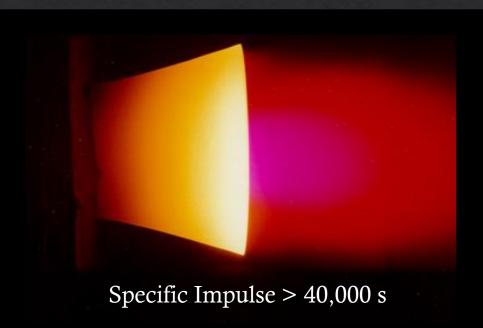
Xenon-fueled

Today's ion engines have 10X the exhaust velocity of the best chemical rockets

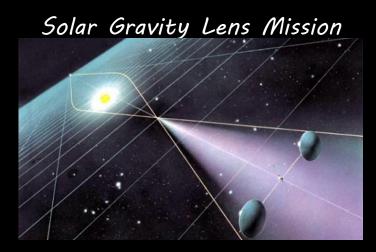


Lithium-fueled

Our ion engines will have 10X the exhaust velocity of the best ion thrusters



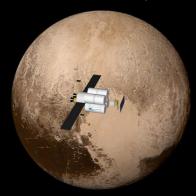
What Might this Architecture Be Able to Do?



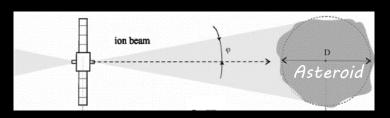
Human Missions to Jupiter



Pluto Orbiter Mission



Planetary Defense—Ion Beam Deflection





Three Key Features of Our Proposed Architecture to Go Fast

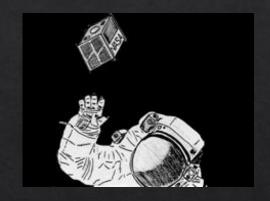
1 High Power



Don't carry the power source— laser beam power to the spacecraft



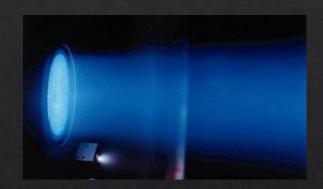
Small Dry Mass

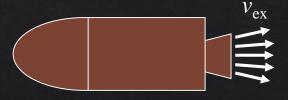


Collect the laser power and convert it to electricity to power the ion drive system



Small Propellant Mass





Increase the exhaust velocity, $v_{\rm ex}$ by a factor of 10 over the best ion engines today



Summary

- The Rocket Equation drives the need for Electric Propulsion
 - Has resulted in 20 countries around the world developing this technology
- Electric Propulsion is in widespread use on Commercial Communication Satellites
- Electric Propulsion is expanding its footprint on deep space robotic science missions
- Electric Propulsion is currently the technology of choice for human missions to Mars
- Electric Propulsion is applicable to most Planetary Defense techniques (KI, nuclear deflection, gravity tractor, laser ablation)
 - It's largest contribution may be through ion beam deflection
- Electric Propulsion may play a dominant role in asteroid mining
- Electric Propulsion, in combination with power beaming, may enable fast transportation throughout the solar system up to approximately the solar gravity lens location